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Forces on rapidly growing vapor bubbles on a wall in forced convection with varying angle of inclination

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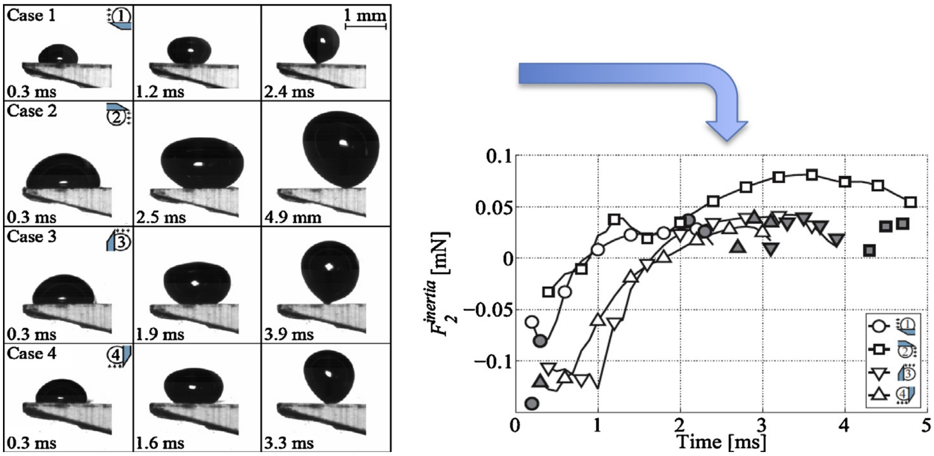
HIGHLIGHTS

- Shape histories of fast growing bubbles hardly depend on the direction of gravity.
- The inertia forces are responsible for detachment of fast growing bubbles.
- Detachment of boiling bubbles against gravity is explained by inertia of the fluid.
- Wall surface heterogeneities facilitate stopping of the contact line and detachment.

GRAPHICAL ABSTRACT



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ABSTRACT

The forces involved in rapid vapor bubble growth are assessed by measurement and analysis of bubble growth in four principal orientations of the boiling surface and channel flow with respect to gravity. The approaching liquid flow is made nearly uniform to warrant the possibility to compute the added mass forces. Almost no difference in shape history is observed between the four cases. This is most remarkable for the case in which the boiling surface is facing downward with respect to gravity. By way of careful shape analysis and extensive force computations, the reason for this remarkable behavior is found to be the crucial role of the inertia force.

1. Introduction

In order to predict nucleate boiling heat transfer, many mechanistic nucleate flow boiling models have emerged in the past 60 years [1,2]. Various of these mechanistic models attempt to quantify the heat transfer from the wall into the bulk liquid by

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Nomenclature

b	generalized coordinate, coefficient in expansion
D	diameter, m
E_k	kinetic energy, J
E_k^{ir}	irrotational part of kinetic energy, J
f	frequency, Hz
F	generalized force, N
g	gravitational constant, m/s^2
h	distance from wall of center of mass, m
H	mean curvature, 1/m
N	number of generalized coordinates
p	pressure, Pa
Δp	overpressure in bubble, Pa
q	heat flux, W/m^2
r	radial distance, m
R	radius, m
T	time, s
T	temperature, K or °C
v	velocity, m/s
V	volume, m^3
x	cos(θ)
x	position vector, m
y	distance of x_{CM} in the direction parallel to the wall to the nucleation site m
β	contact angle
θ	angle in polar coordinate system
ρ	mass density, kg/m^3
σ	surface tension coefficient, N/m
Ψ	matrix of added mass coefficients

Some sub- and superscripts:

b	bubble
CM	center of mass
f	foot
l	liquid
n	degree of Legendre polynomial
sub	subcooling
TF	thin film

incorporating either empirical correlations or predictive models for the number of active nucleation sites on the heated solid interface, the bubble nucleation frequencies prevailing at these sites, and the bubble departure diameter, D_b. In order to determine D_b, mechanistic models relying on force balance calculations require knowledge about the mean bubble radius growth rate, $\dot{R}$ (which will be defined properly in Section 3). The bubble growth rate is combined with an assumption for the moment of bubble detachment. For example, Chen et al. [3] stated that the growing vapor bubble departs from the boiling surface when either the force balance normal to wall or parallel to the wall is "violated" (while excluding the inertial force due to acceleration of the center of mass), which they defined as the moment the force balance would no longer equal zero. This assumption is invalid, since a proper force balance in any direction should always be satisfied. In fact, when the force balance is no longer satisfied, this should lead to the conclusion that one or more of the components in the force balance contains an error or that additional forces are acting on the bubble. The main point is that, unlike sometimes assumed, it is impossible for a force balance alone to yield a correlation for the bubble detachment diameter. Ultimately, a well-defined detachment criterion is required. A certain bubble shape at detachment could be specified by, for example, relating the contact area of the bubble with the wall, the dry-spot area and the bubble volume.

It will be shown in this paper that inertia plays a decisive role in boiling bubble detachment under some circumstances. As not only accelerations, but also velocities are important in the inertia force, prediction of detachment requires estimates of the velocities involved. Our measurements show that the bubble foot is expanding and moving, which makes the velocity of expansion independent of those of translational motion. In particular when dynamic viscosity is low and the Jacob number high, both velocities must be estimated in order to assess the inertia force and to predict bubble detachment. Any proper criterion should therefore be based on estimates of these velocities as well. This insight is of course helpful in constructing and examining detachment criterions.

The main goal of this research is to study the forces involved in growing vapor bubbles. The various accelerations involved in this process, for example the acceleration of the interface and the center of mass, induce added mass force components. The added mass coefficients involved are dependent on the shape of the bubble and the distance of its center of mass to the wall and are, therefore, time dependent during bubble growth. For correct assessment of this force, it is crucial to determine the shape dependent added mass coefficients. Expressions for these added mass coefficients have been derived previously for truncated spheres and free spheres in the vicinity of a plane wall [4,5].

In convective boiling, the liquid flow past a growing vapor bubble will induce a drag force on the bubble. However, this drag force should not be approximated using expressions for fully developed flow over a body, as is often mistakenly done [6]. Vapor bubbles in forced convective boiling have a typical lifetime of 5–10 ms from nucleation up to detachment. During this short time, the liquid surrounding the bubble only moves a distance in the order of the bubble diameter (based on a flow velocity of 0.1 m/s near the wall and a bubble diameter of 1 mm). Therefore, a hydrodynamic boundary layer on the bubble has little time to develop and resulting drag force components are much smaller than those calculated from quasi-steady drag expressions [7].

The present study focuses on individual bubbles boiling on a plane wall with a uniform approaching flow velocity. The experimental setup is constructed in a way that approximates this idealized flow condition as closely as experimentally possible. The orientation of the normal direction of the boiling surface with respect to gravity and flow direction can be varied. The force balance calculations in this work are based on an Euler–Lagrange approach as an alternative to the more commonly applied Newtonian method [4,5,8–11]. One of the most important parameters determined in this study is the overpressure in the bubble, which is in fact the only parameter in the force balance that cannot be measured directly.

First, the experimental setup and procedures will be shown, after which the force balance theory based on an Euler–Lagrange approach will briefly be explained. The vapor bubbles of separate configurations of the boiling surface with respect to gravity are presented, analyzed and compared with each other.

2. Experimental setup and experiments

A closed-loop experimental setup was designed and constructed in order to facilitate flow boiling measurements in near saturation conditions. The setup allows for accurate control of flow, temperature and pressure of the bulk fluid, which is de-mineralized water. Furthermore, a custom made de-aerator allows for optimal de-aeration of the liquid, prior to initiation of experiments. The first key feature of the setup is that it can produce individual vapor bubbles at a pre-defined location in a see-through test section. The second key feature is that the vapor bubble nucleation location is approached by a uniform laminar flow. The last key feature is

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